

IN - 93 - CR
18214/

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Final Report for NASA Project NAGW-1487

Project Title:

X-Ray Emission from Dynamical Shock Models in Hot-Star Winds

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Report Period: From 11/1/88 to 10/31/91

(NASA-CR-194093) X RAY EMISSION
FROM DYNAMICAL SHOCK MODELS IN
HOT-STAR WINDS Final Report, 1 Nov.
1988 - 31 Oct. 1991 (Delaware
Univ.) 6 p

N94-13288

Unclas

G3/93 0182141

I. Summary of Results

The principal aim of this project has been to determine whether X-ray emission from instability-generated shocks in dynamical models of highly unstable hot-star winds could explain the X-ray flux spectrum observed from such hot stars by Einstein and other X-ray satellites. Our initial efforts focussed on extending the earlier isothermal simulations of wind instabilities to include an explicit treatment of the energy balance between shock heating and simplified radiative cooling. We found, however, that direct resolution of cooling regions behind shocks is often impractical, and we thus have also developed additional, indirect methods for determining this shock X-ray emission. The results indicate that the reverse shocks that dominate simple 1-D instability models typically have too little material undergoing a strong shock to produce the observed X-ray emission. Other models with more strongly driven variability from the wind base sometimes show high-speed collisions between relatively dense clumps, and in these instances the computed X-ray flux spectrum matches the observed spectrum quite well. This suggests that collisions between relatively large scale wind streams of different speeds may be more suited to producing the observed X-rays than the reverse shocks arising from small-scale instabilities.

The following gives further details on the work accomplished. A list of papers published over the 3-year term of the project is given in Appendix A. Since expiration of this grant, the work initiated under it has been continued by P.I. Owocki and graduate student Glenn Cooper, whose Ph.D. thesis research on this subject is supported by a NASA graduate fellowship. Completion of this thesis is expected by the end of 1993.

II. Extensions to the Numerical Hydrodynamics Code

1. *Energy Balance*

To calculate X-ray emission directly from a modeled wind structure, we need information on the temperature (and density) structure of the shock-heated regions in the wind. To get this information we added equations for energy balance to the radiation hydrodynamics code in use at the beginning of this project (Owocki, Castor, and Rybicki 1988), which had assumed isothermality. The energy balance includes the effects of compression and expansion (including shock heating) and of effectively thin radiative heating and cooling. We do not account for changes in the ionization balance of the wind material, except for an exponential temperature cutoff in the radiation driving force, to simulate the loss of driving ions to ionization.

2. *Effect of Scattering*

Our second-year report mentioned a new method for calculating the effect of the diffuse radiation field on the driving force, without actually solving the full transfer problem in many lines at each time step. This method, based on a *Smooth Source Function* approximation, has now been fully tested and efficiently incorporated into the code. The method and some results are discussed in reference #21.

III. Calculating Model X-Ray Spectra

1. *Difficulties in Resolving X-Ray Emitting Regions*

Because of the strongly unstable nature of the radiation driving force, a typical model of a hot star wind has a very complex structure, with many shocks and thus many shock-heated regions. This sets severe practical limits on how well such a hot region can be resolved, especially in denser winds (such as those from early O and supergiant stars) where radiative cooling is more rapid and thus the radiative cooling length is very small. Even in relatively thin winds (*e.g.*, from main-sequence B stars), only the hottest, broadest regions can be resolved under current limits on computer resources.

2. *Approximation for Thin Winds*

Work is continuing on this problem, but we find that for thin winds we can obtain useful lower and upper limits on X-ray emission. A direct calculation of X-ray emission from a model wind, ignoring any hot material lost to poor resolution, gives a lower limit. To get an upper limit we turn off radiative cooling in the model calculation, and again calculate X-ray emission directly from the model. This is not as unreasonable as it might appear, since at the temperatures important for making X-rays and at the low densities in a thin wind, the radiative cooling time is much longer than typical dynamical times.

3. *Approximation for Thick Winds*

In thick winds, radiative cooling is rapid enough that the postshock hot region is too narrow to resolve on the numerical grid; in this case the models are nearly isothermal. This makes a direct calculation of X-ray emission impractical. On the other hand, neglecting radiative cooling would severely overestimate the amount of hot material (and thus of X-rays), and would also affect the calculated wind structure.

To circumvent these problems, we have used a *sudden approximation* for stars with dense winds. We assume that the conditions at each shock (shock amplitude, mass flux through the shock) change only slowly compared to the radiative cooling time for shock-heated material. That is, wind material is heated by the shock and then quickly cools back to the background wind temperature. For a particular snapshot in time we can then identify each shock present, and calculate the X-ray emission from a *steady-state* shock of the same amplitude and mass flux. This approximation is less accurate in the acceleration region toward the base of the wind, where the wind velocity and density vary faster. Even so, we believe that it allows useful estimates of X-ray emission.

Preliminary results using each of the above approximations are discussed more fully in reference #22. Briefly, we find that the modeled X-ray spectra vary in time. With the current model and current assumptions, modeled X-ray fluxes are typically smaller than observed, by factors of a few to ten or so. However, occasionally strong shocks with a higher mass flux develop, producing higher X-ray fluxes that can approximately match the observed spectra both in amplitude and in shape.

IV. Current and Future Work

A major budget item of this grant was initial support for graduate student Glenn Cooper, whose thesis research focuses just on this study of X-ray emission arising from instabilities in hot-star winds. Since expiration of this grant, this thesis work has continued under support of the NASA Graduate Research Program. We expect completion of the thesis by the end of 1993, with several journal papers detailing results to be completed shortly thereafter. P.I. Owocki also continues his work on developing more realistic models of the wind instability, with recent efforts aimed at extensions to 2-D with rotation.

Appendix A: Publications Completed under NASA Grant NAGW-1487

Year 1:

1. "Time-Dependent Models of Radiatively-Driven Stellar Winds: I. Nonlinear Evolution of Instabilities for a Pure-Absorption Model", Owocki, S. P., Castor, J. I., and Rybicki, G. B. 1988, *Ap. J.*, **335**, 914.
2. "The Stability of Line-Driven Stellar Winds: IV. Linear Perturbations in Three Dimensions", Rybicki, G. B., Owocki, S. P., Castor, J. I., 1989, *Ap. J.*, **347**, 274.

3. "Physics of Instabilities in Radiatively Driven Stellar Winds", Owocki, S. P., Castor, J. I., and Rybicki, G. B. 1988, in *Physics of Luminous Blue Variables*, Proceedings of IAU colloquium #113, K. Davidson and A. Moffatt, eds. (Kluwer).
4. "The Steady Solutions for a Radiation-Driven Stellar Wind Not Based on the Sobolev Approximation", Poe, C. H., Owocki, S. P., and Castor, J. I. 1988, *B.A.A.S.*, **20**, 1012.
5. "Absolute Instability as a Cause of Intrinsic Variability in Line-Driven Stellar Winds", Owocki, S. P., Poe, C. H., and Castor, J. I. 1988, *B.A.A.S.*, **20**, 1013.
6. "The Steady-State Solutions of Radiatively Driven Stellar Winds for a NonSobolev, Pure-Absorption Model", Poe, C. H., Owocki, S. P., and Castor, J. I. 1990, *Ap. J.*, **358**, 199.
7. "The Steady-State Solutions of Radiatively Driven Stellar Winds for a NonSobolev, Pure-Absorption Model", Poe, C. H., Owocki, S. P., and Castor, J. I. 1989, in *Properties of Hot, Luminous Stars*, ed. C. D. Garmany, Astron. Soc. Pacific, San Francisco, p. 291.
8. "Applicability of Steady Models for Hot-Star Winds", Owocki, S. P., Poe, C. H., and Castor, J. I. 1989, in *Properties of Hot, Luminous Stars*, C. D. Garmany, ed., Astron. Soc. Pacific, San Francisco, p. 283.

Year 2:

9. "Winds from Hot Stars", Owocki, S. P. 1990, in *Reviews of Modern Astronomy*, **3**, Springer, Berlin, p. 98.
10. "Theory of Intrinsic Variability in Radiatively Driven Stellar Winds", Owocki, S. P. 1990, in *Wolf-Rayet Stars and their Interrelations to Other Massive Stars in Galaxies*, K. Van der Hucht and B. Hidayat, eds., Kluwer, Dordrecht, p. 155.
11. "Stellar Winds from Massive Stars: The Influence of X-Rays on the Dynamics" Stevens, I. A., Cooper, G., and Owocki, S. P., 1991, poster paper summary in *Wolf-Rayet Stars and their Interrelations to Other Massive Stars in Galaxies*, K. Van der Hucht and B. Hidayat, eds., Kluwer, Dordrecht, 318.
12. "Instabilities in Line-Driven Stellar Winds: V. Effect of an Optically Thick Continuum", Owocki, S. P. and Rybicki, G. B., 1991, *Ap. J.*, **368**, 261.
13. "The Effect of Viscosity on Steady Transonic Flow with a Nodal Solution Topology", Owocki, S. P. and Zank, G. P., 1991, *ApJ* **368**, 491.
14. "A Smooth Source Function Method for Including Scattering in Radiatively Driven Wind Simulations", Owocki, S. P. 1991, in *Stellar Atmospheres: Beyond Classical Models*, I. Hubeny and L. Crivellari, eds., Kluwer, Dordrecht, p. 235.

Year 3:

21. "Instabilities in Hot-Star Winds: Basic Physics and Recent Developments", Owocki, S. P. 1992, in *The Atmospheres of Early-Type Stars*, S. Jeffery and U. Heber, eds., Springer, Berlin, p. 393.
22. "Time-Dependent Models of X-Ray Emission from Shocks in Radiatively Driven Stellar Winds", Cooper, R. G. and Owocki, S. P. 1992, in *Nonisotropic and Variable Outflows from Stars*, L. Drissen, C. Leitherer, and A. Nota, eds., Astron. Soc. Pacific, San Francisco, p. 281.
23. Fullerton, A. F. and Owocki, S. P. 1992, "Can Non-Stationary Velocity Plateaus Account for Slowly Moving Discrete Absorption Components", in *Nonisotropic and Variable Outflows from Stars*, L. Drissen, C. Leitherer, and A. Nota, eds. (A.S.P. Conference Series), p 177.
24. Puls, J., Pauldrach, A., Kudritzki, R., Owocki, S., and Najarro, F. 1993, "Radiation Driven Winds of Hots Stars – Some Remarks on Stationary Models and Spectrum Synthesis in Time-Dependent Simulations", in *Reviews in Modern Astronomy*, 6, (Berlin: Springer), in press.
25. Puls, J., Owocki, S. P., and Fullerton, A. W. 1992, "On the Synthesis of Resonance Line Dynamical Models of Structured Hot-Star Winds", *Astron. Astrophys.*, in press.